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Management Strategies to Limit the Impact of Bottom Trawling on VMEs in the High Seas of the SW Atlantic

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1. Introduction

For the past nine years, the issue of protecting biodiversity in the deep sea in areas beyond national jurisdiction – the high seas (HS) – has been widely debated by the United Nations General Assembly (UNGA) and in other international fora. The UNGA adopted a series of resolutions, beginning with Resolution 59/25 in 2004, which called on high seas fishing nations and regional fisheries management organisations (RFMOs) to take urgent action to protect vulnerable marine ecosystems (VMEs) from destructive fishing practices in areas beyond national jurisdiction (Rogers & Gianni, 2010; UNGA, 2004). In December 2006 the UNGA adopted resolution 61/105 on Sustainable Fisheries, calling on flag states, RFMOs and arrangements to immediately act for the sustainable management of fish stocks and to protect VMEs from destructive fishing practices (Portela et al., 2010; UNGA, 2007). In 2009, the UNGA adopted Resolution 64/72 reaffirming the 2006 resolution and made it clear that the measures called for in Resolution 61/105 should be implemented, consistent with the 2009 FAO *International Guidelines for the Management of Deep-Sea Fisheries in the High Seas* (FAO Deepwater Guidelines), by flag states and RFMOs. Resolution 64/72 placed particular emphasis on conducting impact assessments of bottom fisheries on the high seas (UNGA, 2009: Paras 119–120).

Recent relevant studies have concluded that bottom fishing may damage or destroy long-lived epifaunal animals such as corals and sponges, reducing the three-dimensional complexity of the seabed and leading to decreased species diversity and faunal biomass (Althaus et al., 2009; Clark & Rowden, 2009; Koslow et al., 2001; Orensanz et al., 2008; Reed et al., 2005; Rogers & Gianni, 2010; Stone, 2006). Due to its characteristics, bottom trawling is likely to have the most serious adverse impacts on vulnerable deep-sea benthic species (Rogers & Gianni, 2010; Weaver et al., 2011). Several authors (Bensch et al., 2008; Coggan et

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al., 2007; Collie et al., 2000a, 2000b; Durán Muñoz et al., 2008, 2009; Kaiser, 1998; Kaiser et al., 1998, 2006; Murillo et al., 2010; Portela et al., 2010; Rogers & Gianni, 2010) have studied the potential disturbance of the seabed by bottom otter trawls and the possible negative effects on the structure of benthic communities.

Following UNGA recommendations and the FAO Deepwater Guidelines (FAO, 2009), the Spanish Institute of Oceanography (Instituto Español de Oceanografía [IEO]) conducted between October 2007 and April 2010 a series of 13 multidisciplinary research surveys on the HS of the SW Atlantic onboard the multipurpose R/V "Miguel Oliver". The main objectives of these campaigns were: i) the quantitative and qualitative description of the biotopes, ecosystems or communities identified as VMEs; (ii) the identification of the vulnerable organisms eventually found in the study area; and (iii) to assess the potential negative impact of bottom trawl fishing on them.

The study resulted in: i) a detailed cartographic and bathymetric mapping of the area; ii) a description of the geological substratum and of the benthic features; iii) the identification and description of the VMEs; iv) the delineating of candidate sites for protected areas supported by geological, geomorphological and biological criteria; v) an analysis of the overlap between fishing activities and VMEs; vi) the analysis of the abundance and distribution of the main commercial species; vii) comparisons between fished and unfished areas using seafloor observations with towed cameras, observations of fishing impacts with a remotely operated vehicle (ROV), sampling of seabed communities in impacted versus non-impacted areas, and documenting by-catch of benthic invertebrates in fishing gear; and viii) the analysis of hydrographic conditions and pollutants.

The project swath-mapped for the first time large areas of the Argentine Continental Margin (ACM) off the Argentinean Economic Exclusive Zone (EEZ) from 41º30´S to 48ºS, obtaining full data coverage of the seafloor in this region between the outermost continental shelf and the middle slope down to 1600 m water depth contour (Figure 1A). This large area of the ACM included two main specific regions: the southernmost region (45ºS to 48ºS), corresponding to a segment of the outer continental shelf and to the upper, middle and low continental slope segments (Figure 1B); and the northern region, (41º30´S to 45ºS) (Figure 2A, B and C), covering only part of the upper and middle continental slope, since the continental shelf is located within the Argentinean EEZ and therefore out of the scope of the study.

Sedimentation and morphology of the outer continental shelf and slope of the ACM are strongly influenced by the Falkland/Malvinas Current (FMC) at depths under than 2500 m. The FMC is generated as a branch of the Antarctic Circumpolar Current (ACC) and flows towards NNE along the ACM (Legeckis & Gordon, 1982). The ACC divides into 2 branches when reaching the South Falkland/Malvinas slope, the oriental branch being the most intense. Over the ACM the current is about 100 km wide and its eastern limit flows parallel to the 200 m isobath (Anon., 2008). The FMC greatly influences the outer continental shelf and slope of the ACM, with an estimated flux between 1 and 2 Sv† towards NNE (Piola & Rivas, 1997; Piola, 2008) and velocities between 5 and 10 cm s^{-1} over middle and outer shelf (Peterson 1992). This important marine dynamic has been corroborated by the sand waves

† The sverdrup is a unit of measure of volume transport (0.001 km^3/s)

(found in the outer continental shelf at 150 m depth oriented SSW-NNE), together with the megaripples (found in the medium slope between 1000 and 2000 m oriented E-W), and the presence of erosive sea bottoms and striking scarps (in the southern zone of our study area between 1000 and 1500 m) (Acosta et al., submitted).

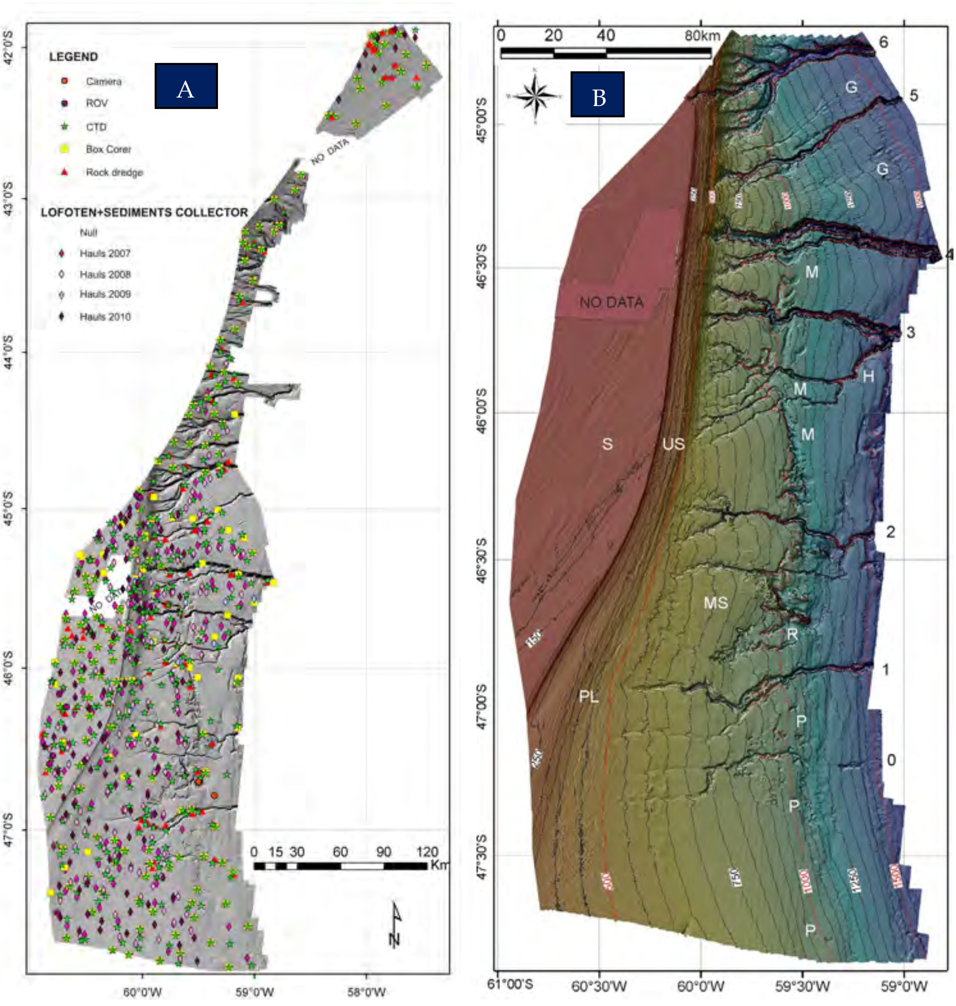

Fig. 1. **A**) Study area with the swath-mapped region and location of the different stations. **B**) Outer continental shelf and slope from 45ºS to 48ºS (southern region). G: gullies; M: moats; MS: middle continental slope; P: pockmarks; PL: iceberg plough marks; R: ridge; S: continental shelf; US: upper continental slope

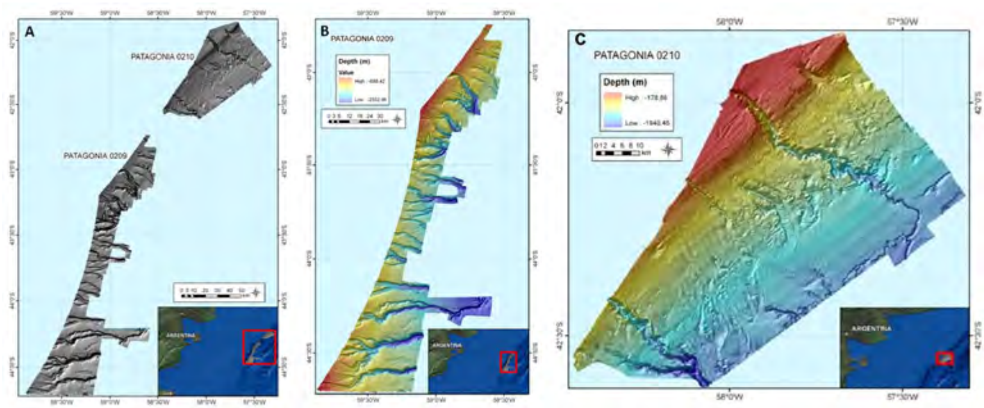

Fig. 2. **A**) Upper and middle continental slope between 41°30´S and 45ºS (northern region) studied in 2009 (**B**) and 2010 (**C**)

Vulnerability is related to the likelihood that a population, community, or habitat will experience substantial alteration from short-term or chronic disturbance, and the likelihood that it would recover and in what time frame. These are, in turn, related to the characteristics of the ecosystems themselves, especially biological and structural aspects. VME features may be physically or functionally fragile. The most vulnerable ecosystems are those that are both easily disturbed and very slow to recover, or may never recover (FAO, 2009). Because of their abundance and sensitivity to damage from fishing activities, cold water coral reefs, coral gardens, sponge beds, and rock outcrops are among the most vulnerable ecosystems.

Bottom trawls can damage the physical structures of the seafloor, particularly impacting rare or fragile corals, sponges and other "sessile" seabed organisms. Several studies (Clark & Koslow, 2007; Rogers, 1999; Stone, 2006; Weaver et al., 2011) have shown that fishing practices impact on the abundance and diversity of the fauna associated with sedentary living communities. Bottom fishing gears destroy long-lived epifaunal organisms such as corals, sponges and other large protruding epifaunal species on the seabed, reducing the three dimensional complexity of the bottom which provides shelter for number of marine species (Etnoyer & Morgan, 2003, 2005; Freese et al., 1999; Stone, 2006). The bottom´s increased complexity provides feeding, spawning and refugia sites for invertebrates and fish (Mortensen et al., 2005; Reed, 2002).

Concerning pollutants, it is important to remember that sediments accumulate contaminants, depending on their morphologic and geochemical characteristics. In general, the concentrations of pollutants increase as particle size decreases (Rowlatt, 1995). Contaminants do not remain permanently linked to the sediments, as they can be released to the water column and become available for the marine biota as a result of physical, chemical and biological processes (Chapman & Wang, 2001). Consequently, as contaminants can have a special impact on VMEs, their study should be included in every descriptive programme for the monitoring and control of marine pollution and environmental impact.

Focusing on marine ecosystems, this chapter mainly addresses geomorphological, benthic and fishing impact matters. However, due to their eventual secondary effects on VMEs, a brief description of the hydrographical and contamination aspects is also presented here.

2. Material and methods

The interpretation of the requirements of Resolutions 61/105 and 64/72 has been largely based on the FAO Deepwater Guidelines, as well as on the criteria defined by the North Atlantic Fisheries Organization (NAFO) and habitat codes from the European Nature Information System (EUNIS) database. The FAO Deepwater Guidelines were developed as practical guidance on what was required to enable fisheries managers to develop sustainable ecosystem-based deep-sea fisheries on the HS, in accordance with international law and agreements.

2.1 Geomorphology

Swath bathymetry data were acquired using a multibeam echosounder Simrad EM-302, transmitting frequencies between 26 and 34 kHz, swath opening of up to 150º, 288 beams and 432 soundings per swath. Data were logged and processed with SIS, Neptune and C-Floor software packages, obtaining a grid resolution of 50 m with full seafloor coverage (meeting the International Hydrographic Organization [IHO] standards for marine hydrographical surveys). Navigation was provided by a differential GPS Simrad GN33 integrated within the ship central navigation system (MDM400). Analyses and representation of bathymetric data were performed with ArcGIS software. Fledermaus advanced visualization software has been used to provide 3D views.

Very high resolution seismic reflection profiles were obtained using a Simrad TOPAS PS 18 functioning on the parametric principle, along swath bathymetry lines, at intervals of 9 and 10 km. This source has two primary frequencies, 15 and 18 kHz and the possibility of obtaining a secondary frequency of 0.5 and 5 kHz. Recorded profiles had a very high vertical resolution (less than 1 m) and penetration ranged from 50 to 200 m in unconsolidated sediments. Seafloor photographs were taken at selected sites using a Nikon D700 digital camera mounted on a framework equipped with a submarine navigation system consisting of a Sea Bird Electronics SBE911plus CTD with an altimeter Benthos PS916D.

2.2 Benthos and sediments

Different gears were used to sample benthic fauna in the study area: a Lofoten bottom trawl fishing gear was used over soft bottoms and bathyal plains during fishing operations, whereas rock and megabox corer dredges served to specifically prospect particular bottom environments whose structures and composition had previously been geomorphologically characterized and identified.

Sedimentological samples were collected mainly using net collectors attached to the Lofoten fishing gear during fishing cruises. An USNEL-type megabox corer was also used (maximum breakthrough of 60 cm; effective sampling area of 0.25 m² [50 cm × 50 cm]) for the benthos surveys. In addition, a few samples were taken using a Bouma-type box corer (effective sampling area of 0.0175 m^2 [10 cm × 17.5 cm]). Both box corer types are designed to take undisturbed samples from the top of the seabed, and are suitable to sample almost every type of sediment. Temperature and redox profiles (Eh) of sediment were immediately performed for the box corer sample after each station. In the laboratory, the granulometrical analysis of the sediment was carried out by dry sieving the coarse fraction (>62 µm) and by sedimentating of the fine fraction (<62 µm; Buchanan, 1984). The organic matter content of the sediment was estimated by the loss in weight of dried samples (100ºC, 24 h) after combustion (500ºC, 24 h).

2.3 Interactions between bottom trawling and VMEs

The 13 research cruises sampled a total of 433 stations (375 bottom trawls and 58 rock and box corer dredges) in the study area, and the presence of VMEs and/or fragile organisms was recorded in 176 of them.

GIS techniques served to aggregate data by cells of 2000 m length, covering the entire area of study. Each cell contains information related to environmental conditions: bottom floor characteristics, geomorphology, mean sea bottom temperature, slope and depth, and biological data (presence of sensitive and/or VME indicator species).

Data were integrated in R statistical software and the BIOMOD package was run to generate an optimized distribution model. To do so, surface range envelope (SRE) method (Busby, 1991) was used for selecting 500 random pseudo-absences in dissimilar environmental conditions, and random forest (RF) method (Breiman, 2001) was subsequently chosen to perform the presence/absence distribution modelling. Predictive performance of the model was checked using the receiver operating characteristic (ROC) curve through multiple cross-validation procedures, splitting original data three times in two random subsets for calibration (80% data) and evaluation (20% data) using as model predictive performance index the mean ROC value obtained from the three repetitions. To detect and quantify overlapping areas, model results were integrated with the fishery footprint, which included more than 14,000 vessel monitoring system (VMS) positions of Spanish vessels fishing in these waters registered between 2001 and 2008.

Moreover, during the whole study, three of the cruises aimed estimation of stock abundance and biomass indices of the main commercial species. A stratified random design with stratum boundaries defined by latitude and depth ranges was applied. Scheduled fishing stations (hauls of 30 min) were performed using a LOFOTEN-type gear of 35 mm codend mesh size. Abundance and biomass indices were calculated using a swept area model. The study area was divided into 13 depth strata further subdivided into 2571 grids of around 5 nm^2. The position of the hauls was randomly chosen prior to surveying each stratum and hauls were allocated according to several criteria previously defined. As above said, the fishing gear was also used as a benthic sampler, complementary to the more specific megabox corer and rock dredges used in the other surveys with no fishing objectives. Density maps of the main commercial species were calculated from catch values (kg), using the *ArcGis Density* tool and applying the Kernel quadratic function (Silverman, 1986) in a way that density values are expressed in kg/0.5h/square surface units, in the present case, 0.0125 x 0.0125.

2.4 Hydrography and contamination

A Seabird-25 CTD probe was used to characterize the hydrographical conditions of the study area. After processing procedures, a total of 406 valid CTD profiles were analysed. The CTD was systematically deployed at fishing stations below 500 m, but not always at greater depths. At each cast, the CTD was deployed to 5 m depth and stabilised for approximately 3 min. It worked in auto-contained mode at frequency of 8 scans·s^{-1}. Once stable, the CTD was brought back to the surface and started profiling at a constant speed of 1 m·s^{-1}. Due to the schedule of the surveys, the CTDs were mainly associated to the spring-summer period.

SeaBird software and standard calibration values were used for pre-processing data and converting to physical units. Subsequently, MatLab served for quality control and post-processing tasks. Temperature and salinity fields at different depths were calculated by using the variational inverse method (Brasseur et al., 1996), initially designed to solve problems with high resolution vertical profiles but irregular horizontal coverage, and implemented in the DIVA package (Troupin et al., 2008) and ODV-4 software (Schlitzer, 2011). DIVA and ODV-4 allowed analysing and interpolating data taking into account coastlines and bathymetry features to structure and subdivide the domain on which the estimation is performed. Calculations were optimized and performed on a finite element mesh adapted to the specific gridding domains.

For the study of contaminants, surface sediment samples (layer between 0 and 5 cm) were collected with a megabox corer grab. The total fraction of sediment (fraction below 2 mm) was analysed for both metals and polycyclic aromatic hydrocarbons (PAHs). Trace metals analysis was performed using the total digestion of the samples with a hydrofluoric acid and aqua-regia mixture in a microwave oven, followed by neutralization with boric acid. Nitric acid digestion was applied for mercury analysis. Quantification was carried out by atomic absorption spectrometry (flame, graphite furnace and cold vapour) (Beiras et al., 2011). Thirteen individual PAHs were measured following the method described by Viñas et al. (2002). The samples were Soxhlet extracted using a mixture of organic solvents. The recovered extracts were treated with activated copper for elemental sulphur removal. A clean-up step was performed by column chromatography using deactivated alumina. The concentration and composition of the PAHs were determined by high-performance liquid chromatography–fluorescence detection (HPLC-FLD) with wavelength programming.

Quality control was assured by the frequent use of certified reference materials as well as by the regular participation in international intercalibration exercises, where our IEO laboratory always obtained satisfactory results.

3. Results

3.1 Geomorphology

About 59,105 km^2 of the external shelf (off the Argentinean EEZ) and upper and middle slope of the ACM down to 1600 m depth contour were mapped (Figure 1A). The study differentiated two main regions (southern and northern), as described in section 1.1.

3.1.1 Southern region (45ºS - 48ºS)

CONTINENTAL SHELF: The outer continental shelf investigated is dominated by sediment ridges oriented in NNE-SSW direction, oblique to the shelf break and changing in its northern part to a N-S orientation. The sand ridge crests were 15 m height and separated by 3 to 4 km. They were considered as relictual of the post-glacial transgressions. Figure 3 shows the presence of low rocky outcrops that seem to be prograded by the sand ridges aforementioned. These rocky outcrops are concordant with flat rocks and rock fragments of sandstones abundantly colonized by different species, as revealed by analysed samples and ROV video recordings.

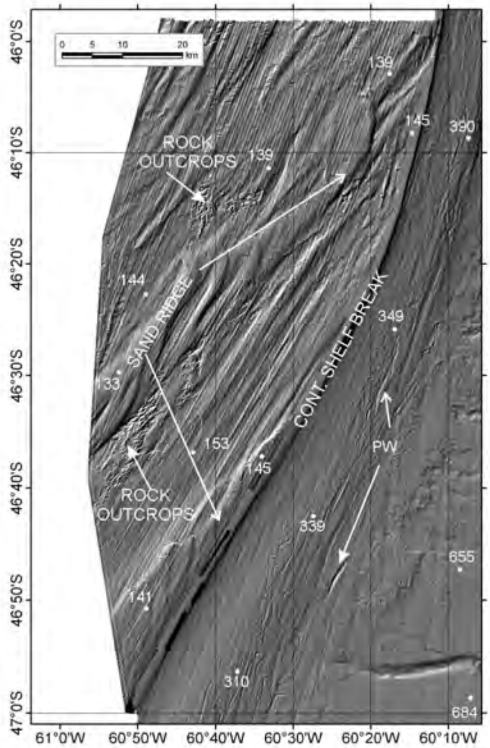

Fig. 3. Rock outcrops and sand ridges in the Patagonian Continental Shelf between 46º10′ and 46º40′S. PW: plough marks; White dots: water depth in m

CONTINENTAL SLOPE: The upper slope is 6 to 20 km wide, has a declivity of 4˚ to 1˚20′ and descends from the continental shelf break (128-200 m depth) to depths between 250 and 750 m. Seven submarine canyons (0-6 in Figure 1B) entrench the upper slope south of 45˚ 40′S, belonging to the Patagonian Submarine Canyon System. Within this area, these canyons and their multiple branches dissect eastwards the upper and middle continental slopes across terraces and steps. At approximately 3.5 km depth, these canyons are collected by a morphologically very diverse slope-parallel SSW–NNE oriented channel, known as the Almirante Brown transverse canyon (Lastras et al., 2011).

South of 45˚20’S the base of the upper slope is scarred by iceberg plough marks. López-Martinez et al. (2011), inferred that the plough marks were probably eroded by icebergs carried northwards by the FMC during the last glaciation (Figure 4).

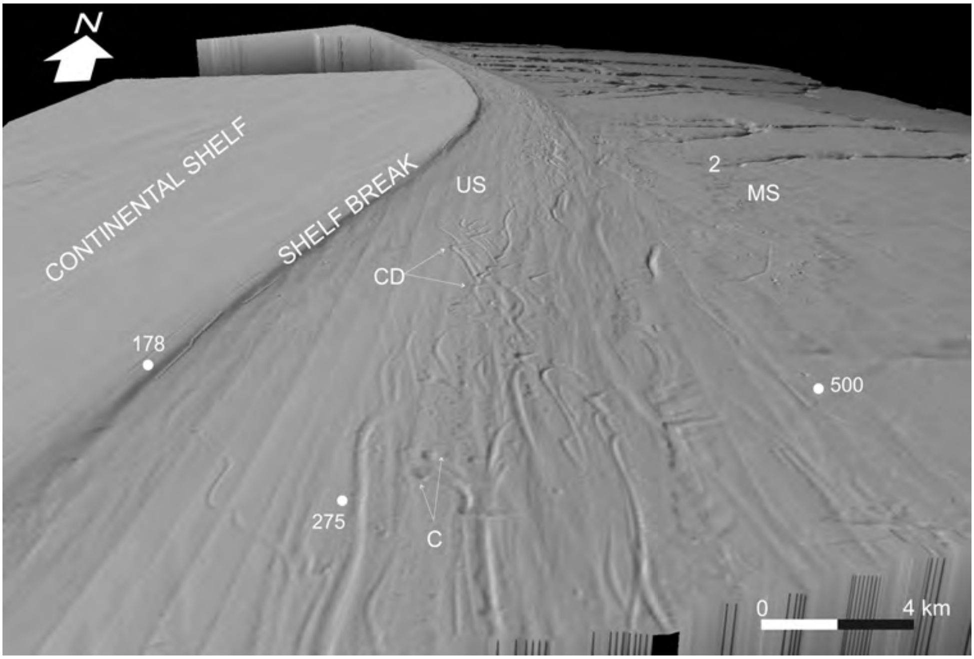

Fig. 4. The base upper slope shows erosion by iceberg plough marks during the last glaciation. US: upper slope; MS: middle slope; C: iceberg craters or pit marks; CD: abrupt change of direction of plough marks; White dots: water depth in meters.

The middle continental slope generally had a gradient of <1˚ and extended from depths between 250 and 750 m to depths comprised between 1600 and 2000 m. This middle slope is the creation of bottom current erosion during the opening of the Drake Passage in the Eocene-Oligocene and the northwards extension of the FMC (Hernández-Molina et al., 2009, 2010; Acosta et al., submitted).

Secondary features carved on the middle slope include plough marks cut by icebergs during the last glaciation on its inner edge at depths of 250 to 550 m south of 46˚20’S (López-Martinez et al., 2011), seven submarine canyons, three sets of gullies, pockmarks created by the expulsion of gas, thin-skinned tectonics south of 47˚20’S, sediment drifts and a belt of bottom current erosion along its seaward edge. Modifying the morphology of the middle slope we also found carbonate mounds capped by cold-water corals, siliceous sponges and bryozoan bioherms (Muñoz et al., submitted).

3.1.2 Northern region (41º30’S - 45ºS)

The southernmost part of the northern region exhibits numerous canyons and gullies in the middle part of its courses, located in the upper and middle slope (Figure 2B) from 179 to

2253 m depth. Figure 5 shows a 3D scheme showing the uneven development of the canyons, as well as their longitudinal extension only covering their middle sections.

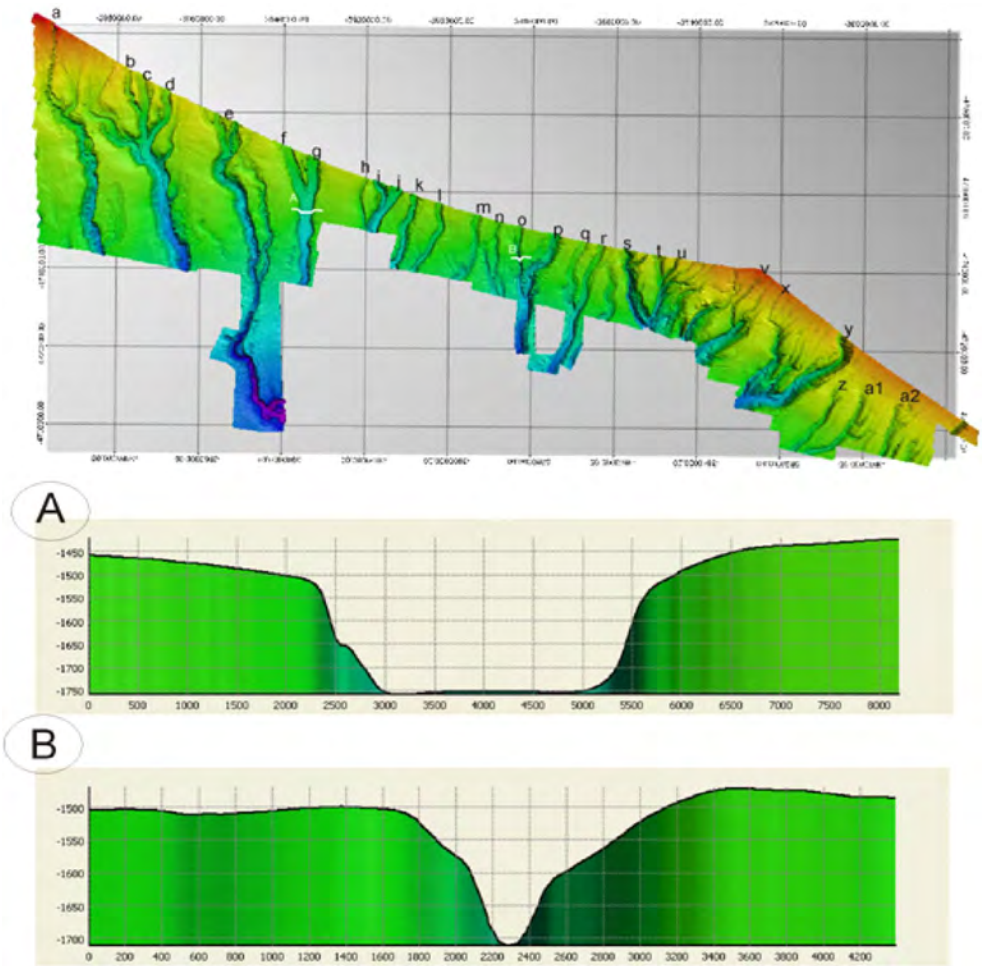

Fig. 5. Color coded DTM of Patagonia 02/09 area (landscape representation). a-y = Canyons. Lower panel A-B = Bathymetric cross section of f/g and o canyons. Note the different cross section in U and V

In the northernmost part, the study depths ranged from 178 m in the outer continental shelf to 1940 m in the middle slope. Figure 2C shows the outer continental shelf with both the head of two main canyons and the presence of a striking field of megaripples and iceberg plough marks. Megaripples with amplitude of more than 25 meters, base widths of 1000 m and crest lengths of more than 25 km are a singular and unique feature covering approximately 780 km^2 of the slope surface, and orientated NW-SE. The existence of this huge field of tractive sediment forms may be interpreted as the result of the action of the FMC front of more than 25 km generating this mega field of sediment waves on the seafloor.

3.2 Benthos

The benthic megafauna caught during the cruises, including both invertebrates as well as phyla Chordata and Hemichordata, showed dominance of the phyla Cnidaria, Porifera and Echinodermata. These phyla are largely considered as vulnerable ecosystem indicators, according to the latest international standards established by the United Nations (UN) and the Oslo-Paris convention (OSPAR). In the Southwest Atlantic studied area, we found a significant diversity of species, habitats and ecosystems, whose special characteristics meet the vulnerability criteria established by international organizations (FAO, UN and OSPAR).

3.2.1 Cold-water coral reefs

Cold-water coral reefs are self-sustained and spatially well defined coral framework sediment systems measuring from tens of metres to several kilometres in lateral extension and up to 40 m in thickness, thus influencing local current regimes (Dorschel et al., 2007). Most cold-water coral reefs occur in deep waters, between 200 and 1500 m, where light is reduced or absent (Freiwald, 2011). Cold-water corals belong to the phylum Cnidaria and include, among others: anthozoan stony corals (O. Scleractinia), black corals (O. Antipatharia), soft corals (O. Alcyonacea), sea pens (O. Pennatulacea), sea fans (O. Gorgonacea) and hydrocorals or lace corals (Class Hydrozoa; O. Anthoathecate) (Cairns, 2007). *Oculina*, *Lophelia*, *Solenosmilia*, *Madrepora* and *Enallopsamia* are known stony colonial coral genera that constitute the majority of deep sea coral reef structures around the world. In our surveys, the most frequent species was *Bathelia candida*, exclusively distributed on southern south America, from Rio Grande (south Brazil) to south Chile (Cairns, 1982; Kithara et al., 2009). This species, less known than *Lophelia pertusa* (EUNIS codes A5.631 and A6.611), but ecologically also very important as bioconstructor. *Solenosmilia variabilis* was also found in minor quantities in the samples.

In the study area, the largest biomass of cold-water corals was located at depths between 400 and 1000 m, sometimes in low slope areas of sandy bottoms, forming both small aggregates and reefs of few metres. In the study area, *Bathelia candida* provided habitat for a great diversity of invertebrates and fishes (ICES, 2003). Dead specimens accounted for an important percentage of the community. These stony corals were colonized by many other species. Associated fauna was dominated by filter-feeders, cnidarians, sponges, molluscs and brachiopods, but also echinoderms and crustaceans (Figure 6).

The most representative species found among Cnidarians were: Order Scleractinia, with *Caryophillia* spp, and *Desmophyllum dianthus*, growing up on the colonial scleractinia, while *Flabellum* spp. *Javania* spp. were found on sediment or small peebles and mollusca debris; Order Alcyonacea, with *Alcyonium* sp., *Anthomastus* sp. among other taxa; Order Gorgonacea, mainly represented by Primnoidae family species as *Plumarella* sp., *Covexella* spp., *Primnoella* spp., *Thouarella* spp., *Dasystenella* sp., and *Fannyella* spp., among other taxa. *Paragorgia* sp. was another abundant sea fan growing on scleractinians, always of small or medium size depending on the substratum surface size and stability.

Order Anthoatecatha, represented by many species of the family Stylasteridae, such as *Adelopora pseudothyron*, *Errina antarctica*, *Errina inferolabiata*, *Errinopsis* spp., *Errinopora cestoporina*, *Cheiloporidion pulvinatum*, *Crypthelia* spp., *Sporadopora dichotoma*, *Sporadopora* sp., *Lepidopora* spp., *Conopora pauciseptata* and *Stylaster densicaulis*.

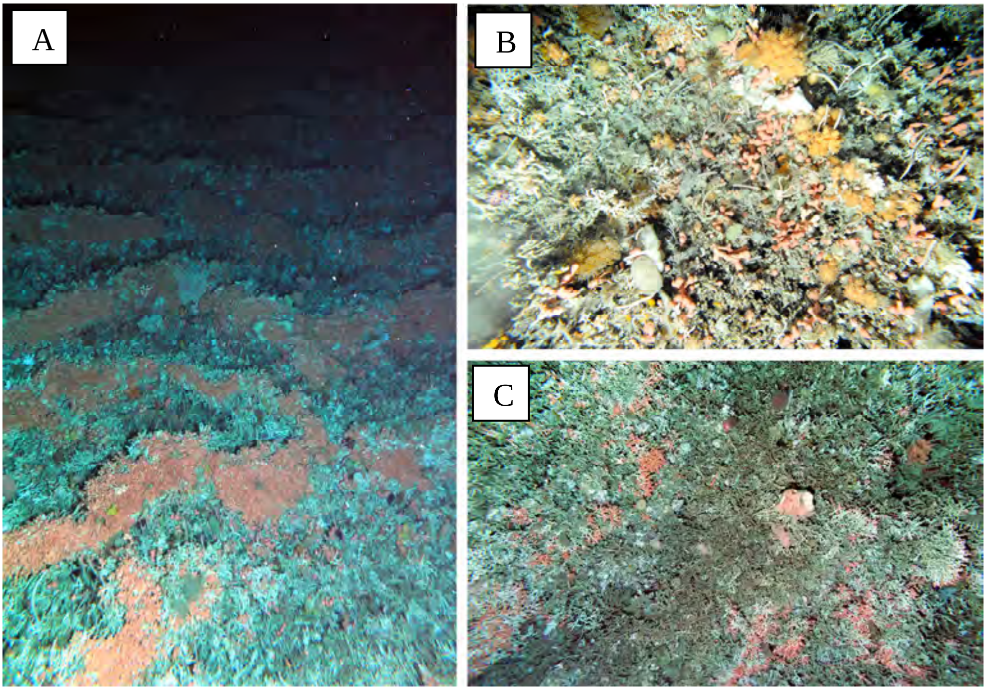

Fig. 6. **A**) View of the outer living zone and inner dead coral framework zone of *Bathelia candida* in the southeast end of the ridge, south of Canyon 2. The polyps (marked in red) evidence the high proportion of living coral on the reef. **B**, **C**) Underwater photographs showing a high density of associated species

Phylum Echinodermata: *Gorgonocephalus chilensis*, *Astrotoma agassizi, Odontaster* sp., *Henricia* sp., *Hippasterias* spp. and *Notasterias* sp. Porifera (*Rosella* spp., *Tedania* spp., *Mycale* spp., *Myxilla spp., Esperiopsis* sp.).

Sub-phylum Crustacea: *Munida spinosa*, *Thymops birsteini*.

Phylum Mollusca: *Bathydomus longisetosus, Miomelon* sp., indeterminate Nudibranchia, *Marseniopisis* spp., *Hiatella* sp., *Limopsis* spp., among other.

Brachiopods, Picnogonida and Ascidians (*Polycarpa* sp., *Pyura bouvetensis*) were also found in the surveys' samples.

3.2.2 Coral gardens

The study photographed cold-water corals both on a hummocky area of the upper slope on the ridge south of Canyon 2 and on individual glacial erratics on the eastern edge of the Perito Moreno Terrace, but also sampled them at stations scattered throughout the middle slope. The bottom photographs showed that the hummocky terrain on the upper slope between 300 and 500 m was due to the presence of soft corals. These organisms were so abundant that the biologists named these sites "coral gardens" (Figure 7). Coral gardens meet the criteria for classification as VMEs (habitats which can occur within deep seabed EUNIS types A6.1 to A6.9). The biological diversity of the coral garden community was very high and contained many species of corals belonging to different taxonomic groups, such as leather corals (order Alcyonacea); gorgonians (order Gorgonacea); black corals (order Antipatharia) –with an exclusive species in the study area, *Dendrobathypathes grandis*-; hard corals (order Scleractinia); and hydrocorals (family Stylasteridae, order Anthoathecata).

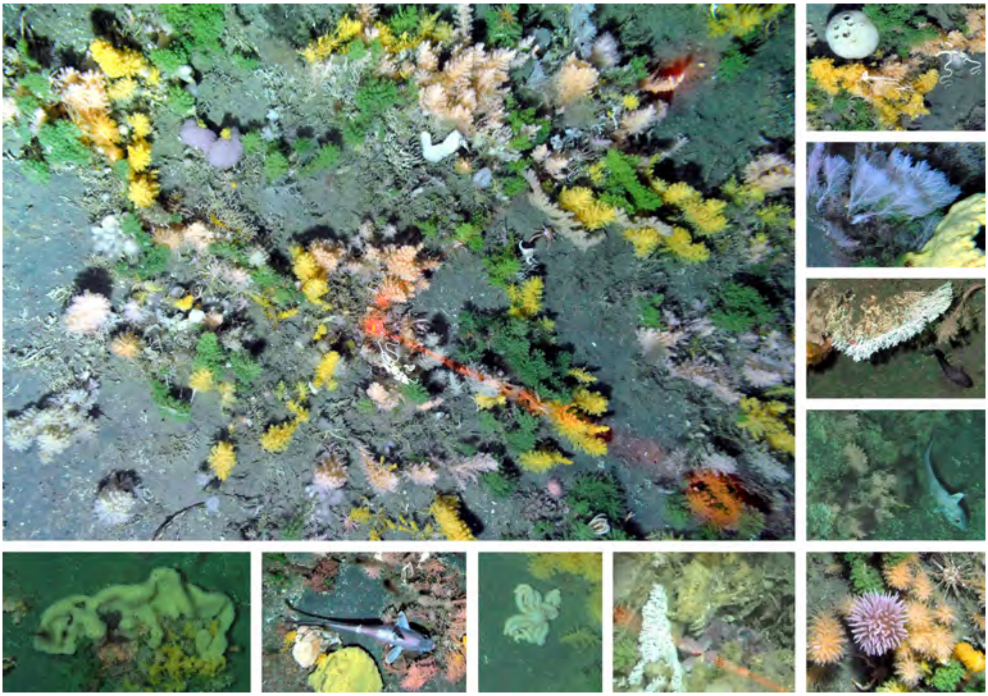

Fig. 7. Coral Gardens bottoms in the study region. These areas could be similar in structural complexity to tropical coral reefs with which they shared several important characteristics, including complex vertical relief and high taxonomic diversity. Views can give an idea of the high biodiversity, mainly Primnoidae with the very abundant species *Thouarella viridis* (green sea fan)

Primnoidae was the dominant gorgonian family in the coral gardens of the study area, represented by several genera and species (Cairns & Bayer, 2005, 2009). The habitat included relatively large numbers of sponge species (with orders Hadromerida and Poecilosclerida especially well represented), although they were not a dominant component of the community. Other commonly associated fauna included echinoderms such as basket stars (*Gorgonocephalus chilensis*), brittle stars (*Astrotoma agassizi, Ophiacantha* spp., *Ophiactis* spp.), crinoids, molluscs, crustaceans and deep-water fishes, such as grenadier (*Macrourus carinatus*).

3.2.3 Sponge beds

Sponge beds or sponge aggregates in deep water (EUNIS Code: A6.62) consisted mainly of two Porifera classes: Hexactinellida and Demospongiae. Their presence was important between 250 and 1300 m (Bett & Rice, 1992), in areas where the water temperature varies between 4º and 10ºC and where currents flow at approximate 0.5 knots. Since sponges have a preference for deep habitats similar to those of cold-water corals, it is common to find both ecosystems coexisting in the same locations. In the study area the presence of deep water hexactinellid sponges belonging to the genus *Rossella*, provided a three-dimensional structure to the seabed on which other species live, hunt or find refuge against predators and existing currents.

Carnivorous sponges (Figure 8) generally colonize hydrothermal vents and abyssal zones, but in the study area they lived at depths not exceeding 1500 m. The different expeditions provided samples in which we identified several species, some of them new to science, belonging to the genera *Asbestopluma*, *Chondrocladia*, *Euchelipluma* and *Cercicladia*, a new genus (Ríos et al., 2011).

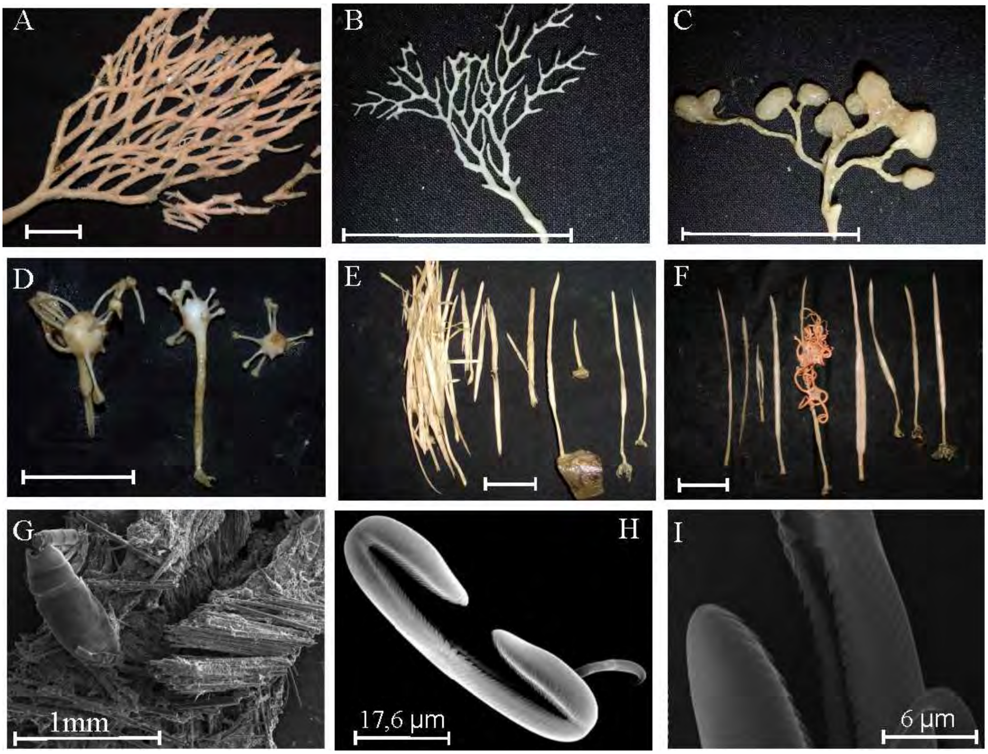

Fig. 8. Study carnivorous sponges. **A**. *Asbestopluma* sp. **B**. *Asbestopluma* sp. **C**. *Chondrocladia* sp. **D**. *Chondrocladia* sp. **E**. *Euchelipluma* sp. **F**. *Euchelipluma* sp. and brittle stars linked to one of the specimens. (Scale **A-F** 5 cm). **G**. Crustacean attached to the sponge spicules of *Euchelipluma* sp. **H**. *Euchelipluma* sp. Spicules: placochela and sigma. **I**. Placochela central detail

3.2.4 Deep marine rocky environments

The deep marine rocky environments can be considered as VMEs because they host rare or endemic species; they are important for the survival, functionality or recovery of fish populations; or due to their fragility and high biodiversity. Our study detected such ecosystem characteristics in different areas. Even if the species' identification of the rock dredge samples is currently ongoing, the preliminary results evidence a high biodiversity on these rocky areas (supported by a number of underwater images taken by the ROV and the submarine digital cameras) (Figure 9). In fact, they host a high number of species belonging to different zoological phyla, including those traditionally considered as vulnerable or protected, such as Porifera, Cnidaria and other invertebrate taxa (ophiuroids, crinoids, asteroids, bryozoans, tunicates, etc).

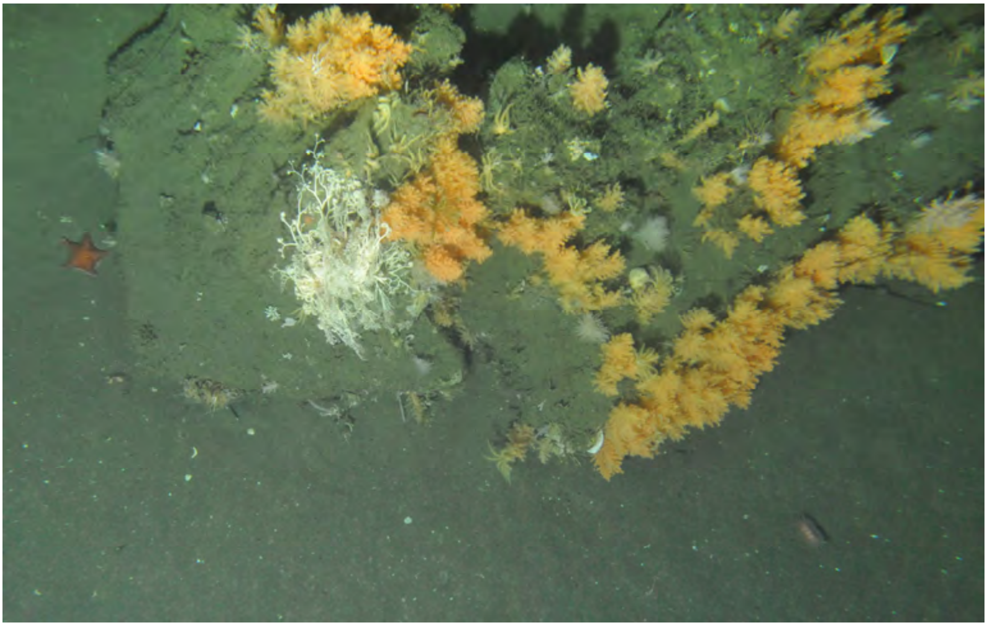

Fig. 9. High biodiverse rocky areas of the continental shelf (135 m). On mud-sand sediments, rocks are colonized by a wide variety of organisms from different zoological groups, competing for the available space. The image shows a large brittle star (*Gorgonocephalus* sp. accompanied of different species of the gorgonian family Primnoidae, asteroids of the genus *Porania*, crinoids, ophiuroids (*Ophiacantha vivipara*), and other taxa (i.e. Porifera and Bryozoans)

3.3 Sediments

Sediment data of the 156 sampled stations showed a predominance of fine sands throughout the study area, with low contents of organic matter, and poorly to moderately well sorted. In general, the thinnest sedimentary types with a higher organic content were found in the southernmost study area, below parallel 46º30'S (Figure 10). Below are detailed the different sedimentary types and their spatial distribution along the whole study area, according to the bathymetric range.

Depths less than 200 m. In the Patagonian continental shelf (59 sampled stations) the sediments were characterized by the presence of all the studied sandy types, even if 30% of the stations were dominated by medium sand and 16% by very fine sand. With a low average of organic content (1.02% ± 0.54%), the sorting varied between good and poor for a moderate average value of the sorting coefficient (S0 = 1.36 ± 0.16). Spatially, larger particle size sediments were found in the central zone of the continental shelf (latitudes between 45º70'S and 46º40'S), separated in the north by fine sands and in the south by also fine sand sediments but with the highest organic content and mud percentage (Figure 10).

Depths from 201 to 300 m. One of the worst studied bathymetric strata, with few sampled stations. The sediment was characterized by the presence of fine sands (Q50 = 0.19 mm ± 0.05 mm) with the lowest organic content of the whole study area, averaging 0.92% ± 0.60%. The sediment was moderately sorted (average S0 = 1.34 ± 0.08). In contrast to the continental shelf, the coarse sediments were almost absent in this stratum, with both the particle diameter moderately diminishing and the organic content moderately increasing from north to south (Figure 10).

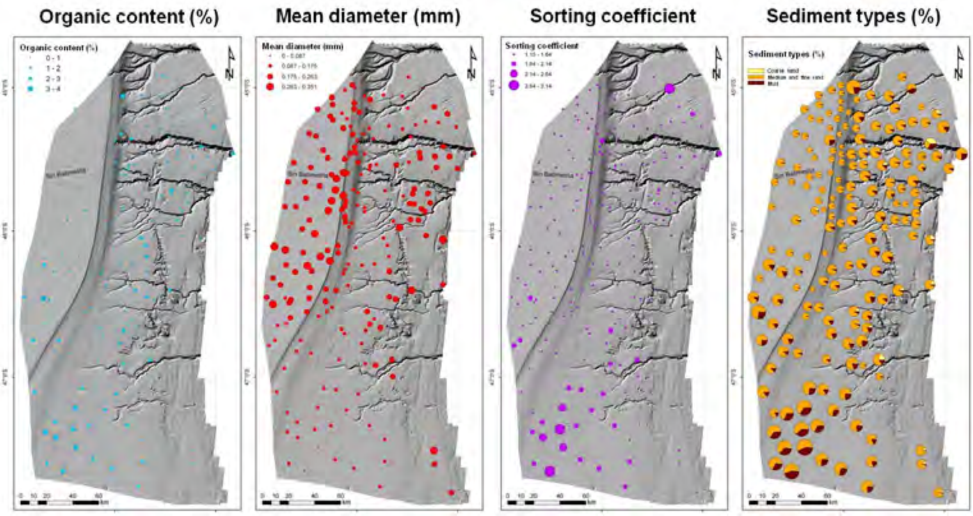

Fig. 10. Spatial distribution of the sediment organic content (%), mean diameter (Q50 in mm), sorting coefficient (S0) and sediment types (%).

Depths from 301 to 400 m. Samples of this stratum come from 14 stations. Again, fine sand is the characteristic type of sediment of this bathymetric range (Q50 = 0.160 mm ± 0.04 mm) and the average organic content is the second lowest value of the whole study (1.01% ± 0.64%). The average value of the sorting coefficient (S0 = 1.31 ± 0.13) evidenced a moderate sorting and was the lowest value of the whole study area. Spatially, the thinnest layers of sediments were associated with high organic matter contents, increasing from north to south (Figure 10).

Depths from 401 to 500 m. This stratum was characterized by the thinnest and muddiest sediments of all the bathymetric strata sampled. This bathymetric range was dominated by the sediments mainly composed of very fine sands (Q50 = 0.120 mm ± 0.04 mm). The average organic content was moderated (2.09% ± 1.09%) and the sediments were the second less sorted (S0 = 1.76 ± 0.58). As observed in the previous bathymetric stratum, the southern stations had the thinnest sediment layers with the highest percentage of organic matter in sediment surface (Figure 10).

Depths from 501 to 700 m. In this stratum samples of a total from 21 stations have been obtained and as in the previous bathymetric range, the sediment is dominated by the presence of very fine sands, with an average mean diameter of 0.130 ± 0.03 mm. The organic content of the sediment was moderated, and is the highest for the whole study (2.19 ± 0.84 %). The sorting of the sediment, in average, was moderated (S0 = 1.59 ± 0.35), with a great range of variation. Spatially, the thinnest sediments in this stratum are found with the highest organic content as the latitude increases (Figure 10).

Depths from 701 to 1000 m. This stratum gathered the highest sampling intensity, due to its largest bathymetric extent. Sandy sediments predominated, and most of them were composed of fine sand (Q50 = 0.160 mm ± 0.02 mm). The average of the organic content was low (1.75% ± 0.47%) and sediments were moderately to moderately well sorted (average S0 = 1.49 ± 0.17). From the spatial point of view, and contrarily to previous strata, the reduction of the granulometry and the increase of the organic content was not so clear as we moved southwards. In addition, this bathymetric stratum had some stations with high percentages of coarse sands in their granulometric composition (Figure 10).

Depths from 1001 to 1500 m. A total of 24 samples were gathered, most of them north to parallel 46°S (Figure 10). This deep stratum was dominated by sandy sedimentary types, mainly composed of fine sands (Q50 = 0.190 mm ± 0.05 mm). The average of the sediment organic content was low (1.44% ± 0.37%) and sediments were moderately to moderately well sorted (average S0 = 1.39 ± 0.11). No clear spatial pattern of distribution was observed in this stratum, where the thinnest sediments (<62 μm) of the whole study were found. As in the previous stratum, we observed high percentages (over 11%) of coarse sands (>500 μm) in the granulometric composition of some stations (Figure 10).

Depths major than 1501 m. A total of 6 samples were gathered in the deepest zone, mainly inside canyons and submarine gullies. The deepest stratum was characterized by the presence of sandy sedimentary types, dominated by fine sands (Q50 = 0.200 mm ± 0.08 mm). The average organic content was low (1.68% ± 0.43%), and the sediments were the worst sorted of the study (average S0 = 3.07 ± 2.99). A study of the sediments' spatial distribution did not make sense, because the stations were located inside the big canyons and submarine gullies transversely crossing the whole study area. There was a high heterogeneity of the sediments between samples, with some stations dominated by thick sands (>500 μm) in their granulometric composition (from 17% to 39.5%), whereas three stations had more than 23% of mires (<62 μm) (Figure 10).

3.4 Interactions between bottom trawling and VMEs

The ROC method described by Zweig & Campbell (1993) was used to measure performance of the chosen model. The area under the curve (AUC) score estimated a model accuracy of 0.913 (1 means perfect prediction and values ≤0.5 mean that prediction does not deviate from random assignment). The most significant variables influencing the distribution of sensitive habitats and/or organisms were, in order of importance: sea bottom temperature, depth, sediment mean grain size and slope.

Output was a VMEs distribution probability map ranging from 0 to 1. ROC threshold chose the cut-off limit that maximized the percentage of presence/absence cells correctly predicted for the evaluation data. Thus, only areas with probabilities over the cut-off limit, set in 0.585, were interpreted as "true presence" areas. The locations of these areas were represented by superimposing onto the fishery footprint, showing the overlapping areas in Figure 11B, under the legend "fisheries impact".

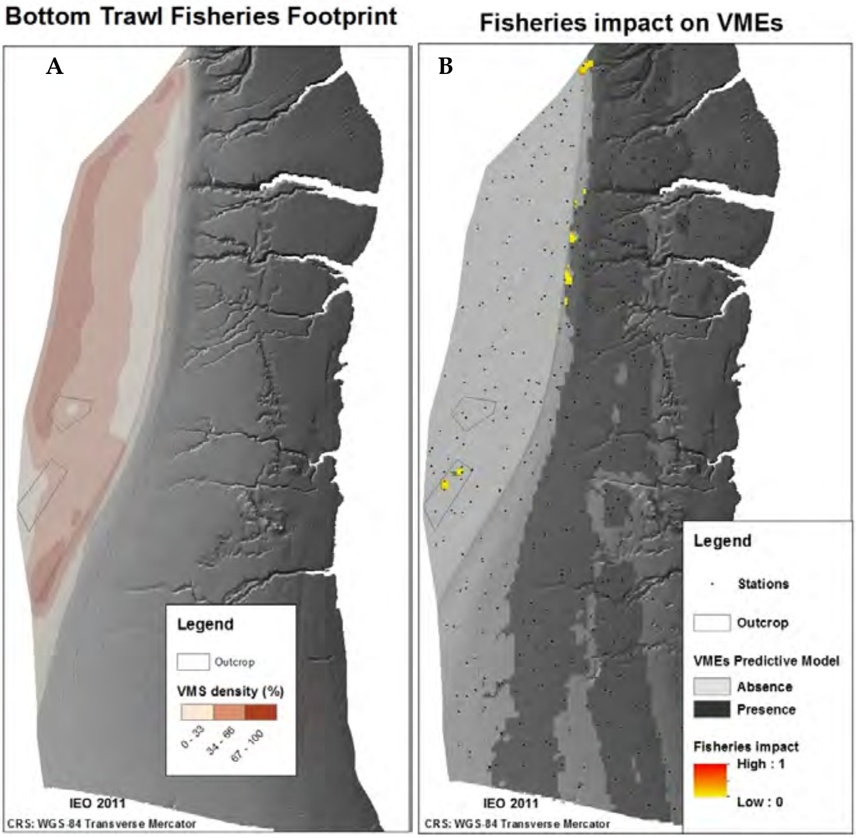

Fig. 11. **A**) Footprint of the fishery in the area between 45ºS-48ºS. **B**) Impact of bottom trawling on VMEs

Regarding biomass assessment and distribution of the main commercial fished species, grenadier (*Macrourus carinatus Günther, 1878*) was identified as the most caught species, with the highest estimated biomass. Grenadier was fished between 200 and 1500 m, but the highest catches were recorded between 500 and 1000 m. The bathymetric distribution range of this species is located away from the usual fishing grounds for the Spanish bottom trawl fishing fleet (shallower) (Figure 11A) so, in spite of being the most abundant species, it is not a target species for the Spanish fleet, which mainly targets shortfin squid (*Illex argentinus Castellanos, 1960*) and Argentine hake (*Merluccius hubbsi Marini, 1933*) in the study area. The maximum catches of shortfin squid, distributed throughout the continental shelf and slope, mainly occurred in hauls between 300 and 500 m depth. Catch distribution of hake clearly indicated its shallower bathymetric range (<200 m), corresponding to the trawls over the continental shelf. Figure 12 shows the catch distribution (kg·haul^{-1}) and the density maps for these three species.

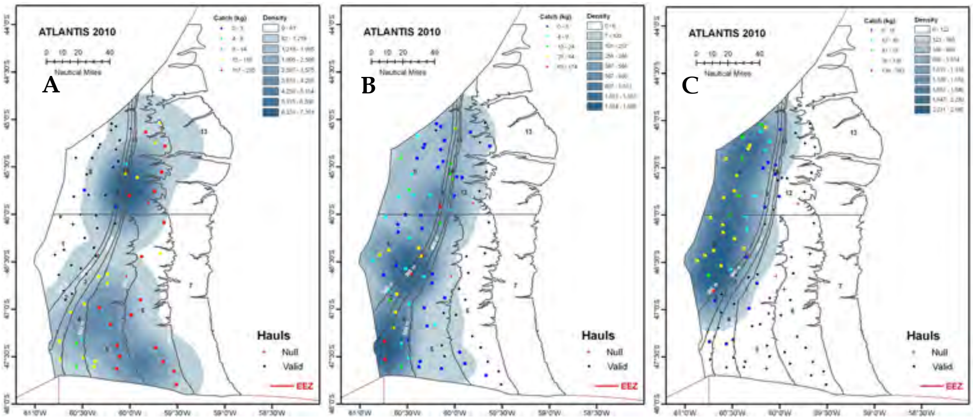

Fig. 12. Catch distribution (kg/haul) and density maps of grenadier (**A**), shortfin squid (**B**) and Argentine hake (**C**) obtained in the 2010 survey

3.5 Hydrography and contamination

Surface temperature and salinity intervals ranged from 8ºC to 15ºC and from 33.4 to 34.2, respectively. Warmer and less salty waters were located over the continental shelf, while colder and saltier waters were distributed over the slope, in the southeast part of the study area. Surface temperatures showed seasonal differences. Below the thermocline, waters became more homogeneous (temperature from 2.5ºC to 5ºC, salinity from 34.0 to 34.5), with subtle differences compared to those of warmer waters close to the slope. CTD data evidenced that the water characteristics resulted from the mixing of the sub-Antarctic waters with the water from the coastal continental discharges. As shallower waters are continuously modified by the atmospheric exchanges, the structure of the thermohaline field at the studied area showed seasonal differences in their stratification, mainly associated with the timing of the surveys, but also with bathymetry (platform/slope/ocean) and latitude (Brandini et al., 2000; Anon., 2008).

DIVA analysis showed small differences and patterns, that had probably been masked by a traditional objective analysis, such as the slight temperature and salinity differences found in the southern part of the latitudinal section (Figure 13) associated to sub-Antarctic waters. Horizontal field at surface (Figure 14) clearly showed the frontal area linked to the continental slope: warmer and less salty waters near the coast and colder ones eastwards, out of the continental slope. Similar patterns were observed at depth, with the FMC flowing along the continental slope and transporting sub-Antarctic waters northwards between 55ºS and 39°S-36ºS (Bianchi et al., 1982; Forbes & Garrafo, 1988; Lusquiños & Schrott, 1983;). The principal core of the FMC is located between 150 and 600 m depth, showing typical temperatures between 4°C and 5ºC and salinities between 34.1 and 34.2 (Piola & Gordon, 1989). This water mass interacts, almost permanently, with shelf bottom waters, which acquire sub-Antarctic characteristics. Our results are in agreement with the hydrographical descriptions found in the bibliography for this area.

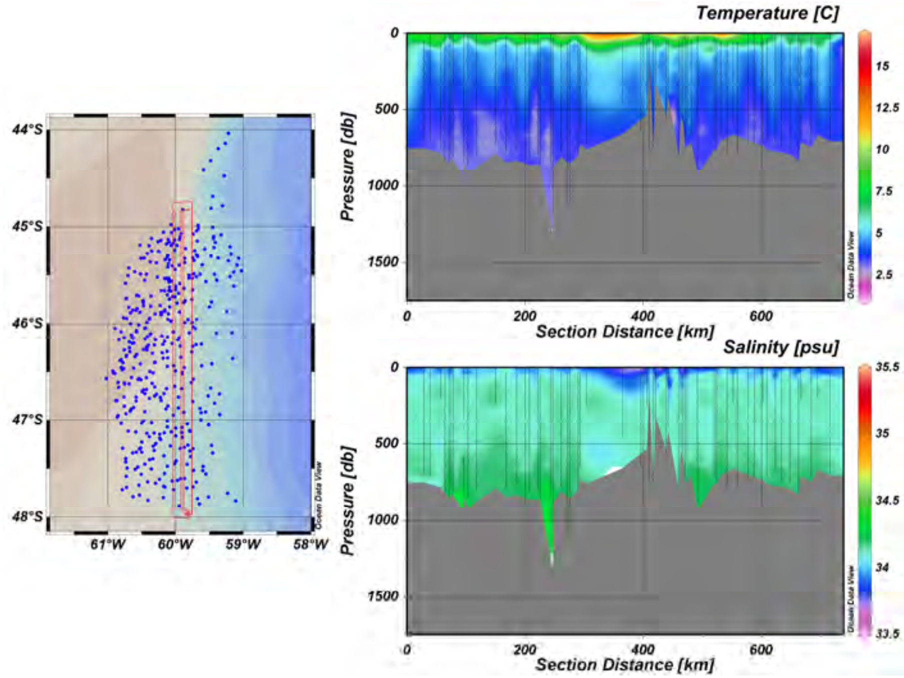

Fig. 13. Latitudinal section (South to North) showing zonal variability and bathymetric stratification. Shallower waters are fresher and warmer, probably due to coastal discharges. Southern parts of the section show colder and saltier waters coming from the Antarctic Ocean

In lower latitudes, and also over the slope from north to south, the observed water characteristics were in agreement with those of the Brazil current that transports subtropical waters (S>35.0 and T>16ºC) up to its convergence with the FMC defining the Subtropical Confluence (36ºS -38ºS) (Gordon & Greengrove, 1986).

Metals and PAHs occur naturally in oceans, rivers and soils. However, the continuous increase of their concentration in estuaries and coastal zones, and therefore in marine organisms, is mainly due to anthropogenic inputs (Harvey, 1997; Kumar et al., 2008). Some metals, like Fe, Cu, Zn and Mn, are essential for organisms, but they become toxic when exceeding a certain concentration. Other elements, such as Hg, Pb, Cd, As and Cr, are not necessary for any metabolic function and become toxic even at very low concentrations. One of the most serious consequences of their continued presence is their accumulation through the food chain. On the other hand, hydrocarbons are extremely toxic to marine life and, those having a high molecular weight produce highly carcinogenic metabolites when they are incorporated into the biota (Long et al., 1998).

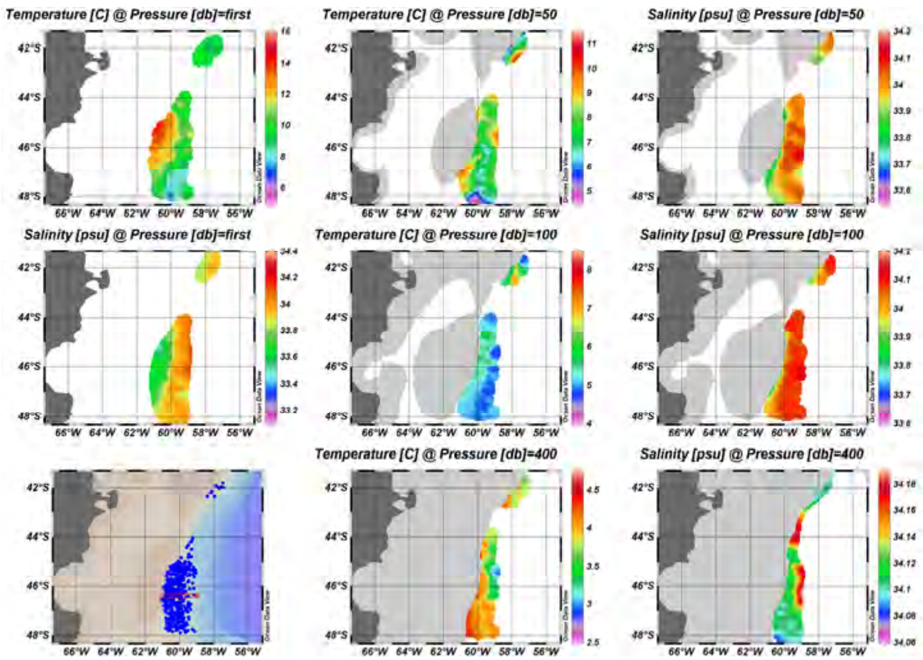

Fig. 14. Horizontal mapping of temperature and salinity at different depths

Low concentrations of trace metals were found in most sediments of the sampled stations (Table 1). Sampling sites were many kilometres from anthropogenic inputs, therefore it was not expected that sediments would be contaminated at most of the stations. In general, higher levels of metals have been obtained in the muddy samples with the highest percentage of organic matter, corresponding to the area to the South of study. In Figure 15, spatial distribution of Cu, Zn, Mn and Al are presented. Al, Fe or Li were determined to recognize natural variations in the trace metal concentration due to natural variation in sediment texture and mineralogy. Trace metal concentrations varied considerably, as it would be expected with a varied mineralogy. The enrichments in different areas are due to complex natural transport and biogeochemical processes, not to anthropogenic sources.

PAH concentrations (Table 2) were very low, even under the Limit of Quantification (LQ) for some of the analysed PAHs in most of the samples. However, we must specify that for most of the samples only the lighter (low molecular weight) and more hydrosoluble PAHs could be quantified, while the heavier and more hydrophobic ones (generally originated in combustion processes) were hardly detected. This situation is typical of areas situated far from the impacts of anthropogenic inputs. Some PAH isomer pair ratios (Phen/Ant and Fl/Pyr) were used to identify possible sedimentary sources and the different surveys were represented in different colours (Figure 16). As expected, due to the distance of the study area from the coast, no samples evidenced PAH due to grass, wood or coal combustion, but three different areas can be identified in Figure 16: samples from the area sampled in campaign 12/07, with petrogenic PAHs origin; samples from the area sampled in campaign 01/08, with pyrolitic-petrogenic PAHs; and samples from surveys 10/08 and 11/08, with PAHs with a more petroleum combustion origin.

	Al	As	Cd	Cu	Cr	Fe	Li	Mn	Ni	Pb	Zn	Hg
Mean	4.97	6.99	0.082	7.40	53.04	2.16	25.09	377	9.46	7.64	39.08	0.011
Median	4.81	5.71	0.069	7.56	39.70	1.86	25.00	373	9.41	7.68	38.60	0.010
Range	1.57- 8.10	2.65- 18.90	0.022- 0.291	<2.00- 14.50	8.03- 230	1.18- 6.74	7.74- 46.80	204- 734	1.62- 18.80	2.37- 30.90	17.70- 72.40	<0.001- 0.113

Table. 1. Summary of the concentrations of trace metals (mg kg $^{-1}$ dry weight, except Al and Fe, in percent) in surface sediments

	Phen	Ant	Fl	Pyr	BaA	Chrys	BeP	BbF	BkF	BaP	BghiP	dBahA	IP
Me-dian	2.13	0.49	1.45	1.97	0.49	0.79	0.98	0.65	0.49	0.39	0.90	0.75	1.24
Range	<LQ- 13.2	<LQ –2.71	<LQ –3.41	0.29- 14.9	<LQ –1.45	<LQ –1.95	<LQ –3.57	<LQ –3.68	<LQ –1.13	<LQ –1.03	<LQ – 7.13	<LQ – 0.75	<LQ –1.24
LQ	0.33	0.12	0.69	0.21	0.27	0.39	0.78	0.48	0.36	0.27	0.57	0.51	1.08

Table. 2. Summary of the concentrations of PAHs (µg kg^{-1} dry weight) in surface sediments. The 13 analysed PAHs were: phenanthrene (Phen), anthracene (Ant), fluoranthene (Fl), pyrene (Pyr), benz[a]anthracene (BaA), chrysene (Chrys), benzo[e]pyrene (BeP), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[a]pyrene (BaP), benzo[ghi]perylene (BghiP), dibenz[a,h]anthracene (dBahA), and indeno[1,2,3-cd]pyrene (IP). LQ: Limit of Quantification

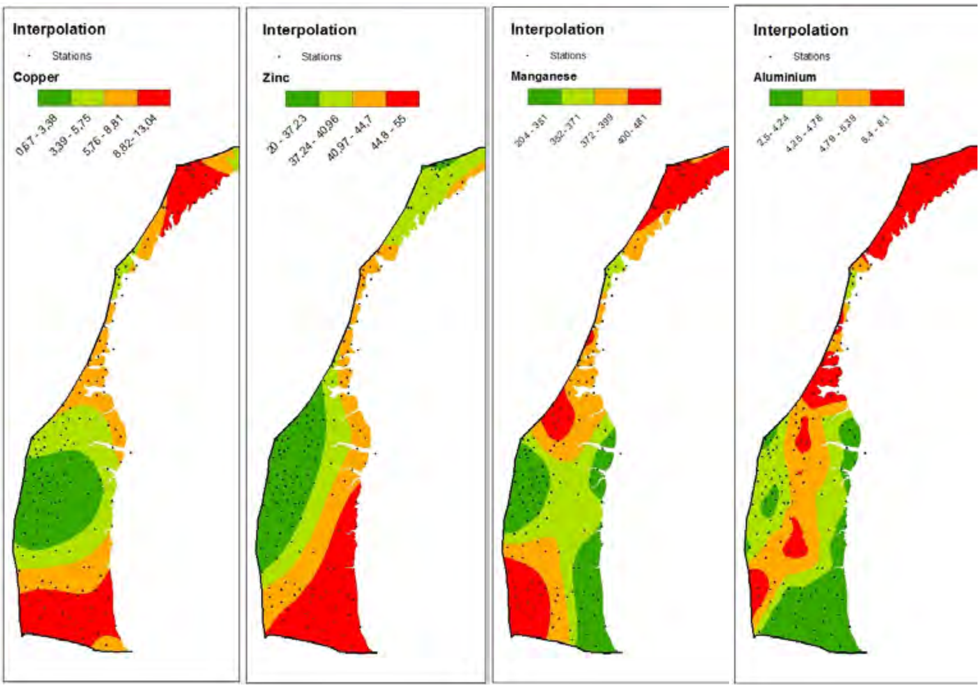

Fig. 15. Spatial distribution of copper, zinc, manganese and aluminium. Values are given in mg kg $^{-1}$ dry weight, except for Al (in percent)

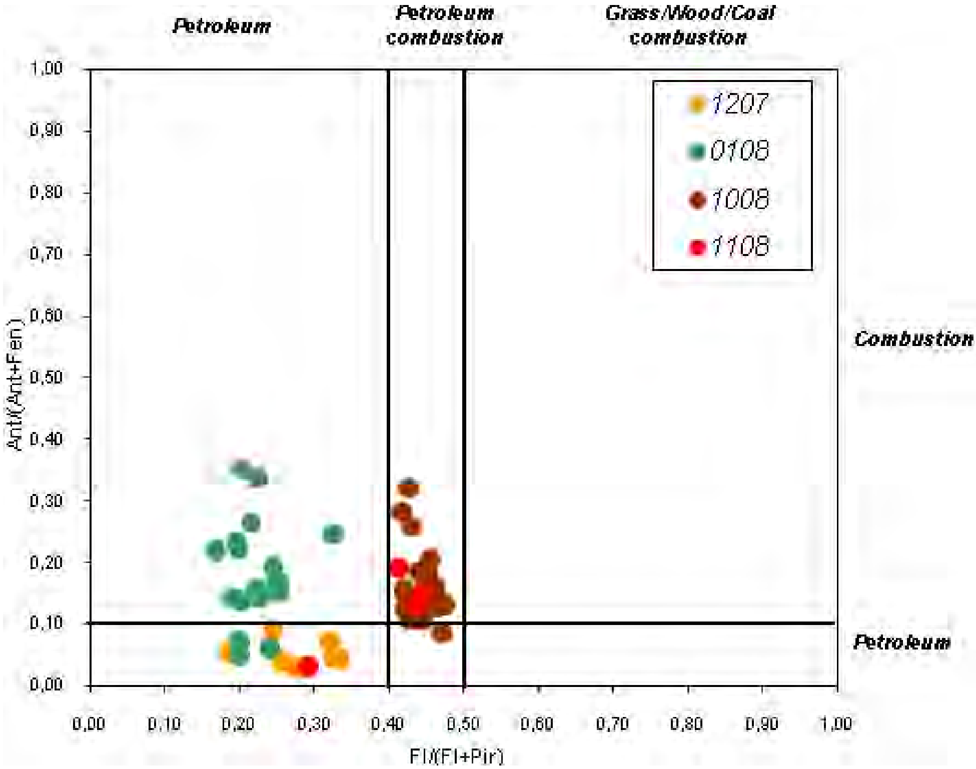

Fig. 16. Isomer ratios to identify PAH sources

4. Conclusion

The series of 13 multidisciplinary research surveys on the HS of the SW Atlantic have allowed the identification of the following main geologic and geomorphologic types that could be considered as mega-habitats (FAO, 2008) or ecotopes (UNGA, 2009):

i. Rock outcrops on the continental shelf made of rock slabs (sandstone) and a deep outcrop located in the middle slope, between canyons 1 and 2 (EUNIS codes A6.1, A6.7);
ii. Mounds (EUNIS code A6.75) located on the top edge of a bend in canyon 2, morphologically corresponding to carbonate mounds or recifal structures;
iii. Rough and hummocky sea floor associated with seepage of fluids (EUNIS code A6.9) located on the upper slope and in the northern third of the study area;
iv. Cold seeps and mud volcanoes in the middle slope of the southern third of the study area, where there were numerous pockmarks (mega-pockmarks due to their size);

v. Numerous canyons and gullies that have been mapped throughout the whole study area. The complex geological and hydrological structure associated with these canyons makes them considered as mega-regions in which habitats are likely to contain vulnerable species.

Biological diversity associated with reefs of *Bathelia candida* is around three times those of the surrounding seabed, indicating that these reefs create biodiversity hotspots and increase densities of associated species (ICES, 2003). In general, deep-sea bottoms vulnerable habitats (as those described above) or special geological structures (as seamounts or canyons) are structurally complex habitats known to sustain high densities and diversity of megafaunal organisms. Our results seem to support the hypothesis that the deep-sea environment is a small organism habitat. In the study area, these habitats host a much higher biodiversity compared to adjacent areas. The complex three-dimensional habitat structures (coral gardens, sponge beds and *Bathelia candida* reefs in particular) provide a multitude of micro-niches favouring the sustainability of an associated animal community by providing enhanced feeding possibilities, hiding places and nursery areas.

In the study area, vulnerable species are mainly distributed in areas located between 400 and 1000 m depth, where the sea bottom temperature ranges from 2.7ºC to 4.5ºC and the seabed sediment grain size is up to 2.3 (Q50). Alternatively, vulnerable species can also be found in outcrop areas of the continental shelf and in some restricted zones of the slope and at the head of canyons. Density maps (Figure 12) of the main commercial species display their geographical distribution and the areas where fishing operations targeting them take place. The Spanish fishing fleet mainly targets hake, distributed along the continental shelf, and shortfin squid, found in the upper slope at depths <500 m. Grenadier, the most abundant species in the study area, is not a target species for this fleet, because it mainly lives deeper than 500 m, where the presence of VMEs was found to be more abundant.

The analysis of the fishery footprint and the defined distribution of VMEs evidenced that Spanish bottom trawling fleet on the HS of the SW Atlantic has a negligible impact on identified vulnerable species or VMEs in the study area. The lack of commercial fishing data of other bottom trawling fleets also operating in this region (i.e. Poland, former USSR and GDR, etc.), makes it impossible to ascertain if VMEs are known or likely to occur in HS areas where bottom fishing takes place, or whether fishing practices are significantly damaging them. Moreover, we do not know if the observed absence of VMEs in the Spanish bottom trawling fishing grounds is a consequence of the impact of previous fishing activities or is due to other reasons.

The research undertaken and its main findings led to the delineating of several areas to be protected, according to biological and geological criteria adopted for the quantitative, qualitative and geographic description of the areas with the presence of organisms classified as vulnerable. Indeed, a specific scientific advice was made to the Spanish Government to protect areas meeting both biological and geological criteria.

Nine areas or regions (Figure 17) along the Patagonian Shelf and slope were identified as VMEs and were designated as candidate areas for closure (a total of ~41,300 km^2). According to this scientific advice, the Spanish Government implemented a fishing ban for the Spanish bottom trawling fleets in the high seas of the SW Atlantic on 1st July, 2011.

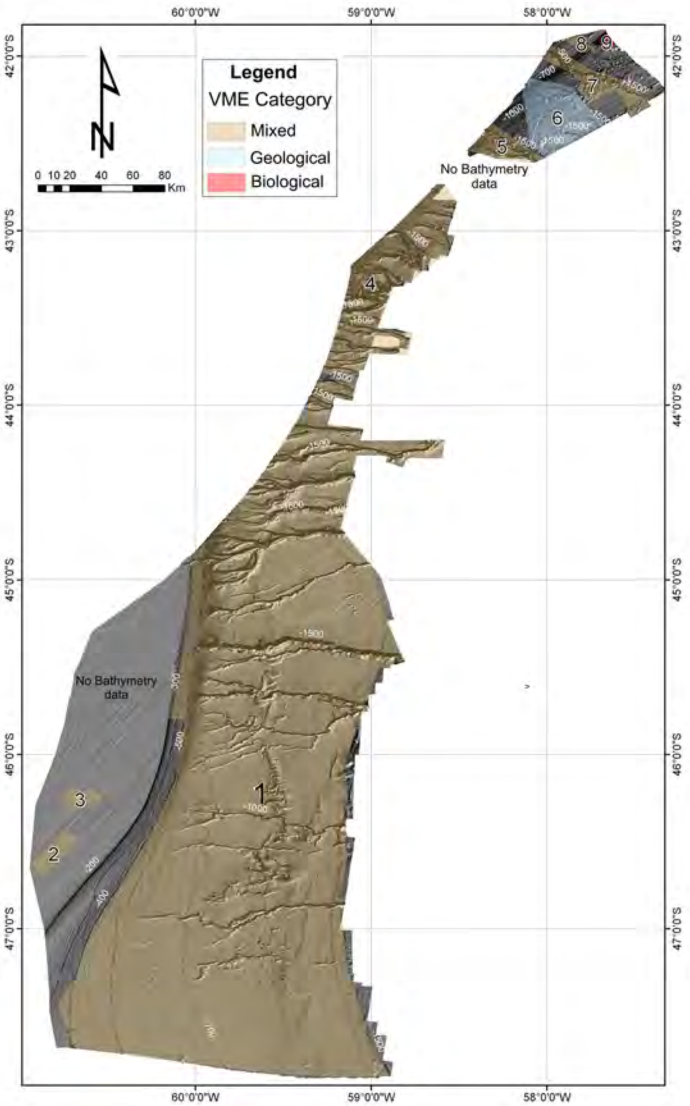

Fig. 17. Candidate sites for protected areas in the HS of SW Atlantic

5. Acknowledgment

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